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DESIGN FOR VARIETY: A REVIEW IN METHODS TO ESTABLISH A PRODUCT FAMILY ARCHITECTURE

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Abstract

This article presents an overview of research in product variants design. The articles selected present methods to solve the challenge of establishing product variants, and are selected to be of help for a design team. Both modularity and platform design have been discussed for quite some time, but in recent years discussions have increased. The methods developed over time have different purposes and are intended for optimising the product in different life-phases. Different design methods are therefore discussed, with an indication of which design phases they position them selves in. They are compared to the three different points of view; functional-, technical- and physical, that illustrates the product development process from establishing customer's needs to the manufacturing and supply chain of the family. The majority of existing methods are working on transforming the customer's needs into the product family and very few methods take the next steps and maps it to the manufacturing, maintenance and recycle processes.

1 Introduction

The evolution in product development is changing from focus on mass production to mass customisation. This change has led to the development of different methods to establish product design that fulfil the individual customers' needs and simultaneously maintain the benefits of mass production. The points of view used in these methods are very scattered as to where in the life-cycle they have their focus and from which abstraction level; strategic to operational. For "one at a time" product there exist a uniform design methodology for all the life phases [Ulrich & Eppinger 1995 and Pahl & Beitz 1996], but they are not comprehensive enough to cover all the areas and detail levels involved in establishing a product family architecture (PFA). A product family consists of multiple products, designed to enter the market at different times or in different categories. Since this involves making decisions for many products at the same time, the economic risk is higher as well as the profit if it succeeds. To improve the chances of doing the right thing at the right time, proper methods are needed.

This review article will present the latest methods to establish a PFA. The selected articles are on the operational level and present methods that are useful for a design team in solving the challenges of designing a product family. The methods are related to modularisations-, product platform design and how to handle the technical "language" needed to map all information into a product family. Articles related to development of only "one at a time" products are not included. All the articles are from well-recognised journals, conferences and design books. The articles selected have all methods that focus on solving the challenge of establishing a family architecture.

1.1 The fundamentals in design for variation

When it comes to transforming design strategies into products, much has happened since the mid- nineties. [Ulrich 1995] was one of the first to clarify the importance of product architecture and that establishing the correct product architecture is a key driver for the performance of a manufacturing firm. He defines *"product architecture as the scheme in which the function of a product is allocated to its physical components"*. With this it follows that the specified function may interact with the physical component in many different ways. Ulrich argues that the major types of typology are modular- and integral architecture. A modular architecture includes a one-to-one mapping from function to physical component, while an integral architecture has a complex mapping, fig. 1. Viewing this in the context of a product family [Sanderson and Uzumeri 1997] define a *"product family as a set of models that a given manufacturer makes and consider to be related"*. This is a very broad definition, but by adding the need to have a high degree of reuse in creating the product variants, [Maier and Fadel 2001] define a product family as: *"... a group of products that shares some common technology"*. This family may be designed with; modularity and product platform approach. Modularity is by [Ulrich and Eppinger 1995] defined *"as chunks (subassemblies) that implement one or a few functional elements. The interactions between the chunks are well defined and are general fundamental to the primary function of the product"*. A well designed modular structure can allow changes to one chunk without affecting the rest of the design. Product platform is by [Meyer M. 2002] defined as *"a common subsystem or subsystem interfaces that is leveraged across a series of individual products by means of shared product architecture"*. A more comprehensive definitions of platform is presented by [Kristjansson et.al. 2004]

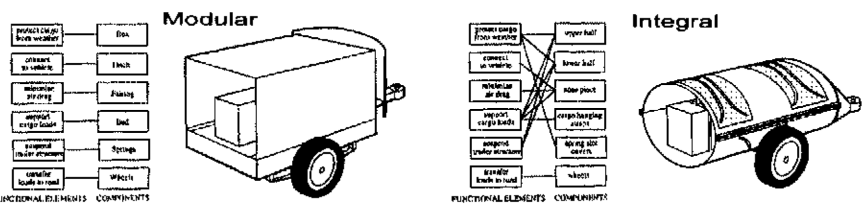


Figure 1: Description of the scheme of modular and integral mapping from functional elements to physical components, [Ulrich 1995]

Establishing the correct product architecture for the product family is a difficult task, as different approaches can be taken to create the variants as well as which life-phases to include in the design process (manufacturing, assemble, use, service and recycle). Each product in the family must be evaluated against their meeting of the life phases in order to find the best common approach. Many different design methods have been proposed and some of them will be discussed further in the text. A review of general product development literature can be found in [Krishnan and Ulrich 2001]. They cover design methods as well as design strategies with a broad view on this academic field. The question of the amount of variety the firm should provide to the marked, and the reasons for why the customers seek variety is discussed in [Ho and Tang 1998].

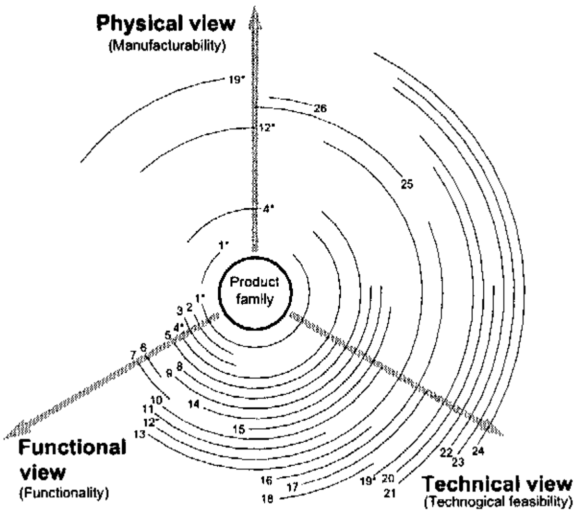
2 Design models

To model a new and slim design assortment there is a need to define the current status. A "picture" of today's products assortments gives valuable insight in this. Such a picture may be taken from different points of view in the design process, so that it can include more than only the bill of materials. The cromosommodel [Andreasen 1992] that describe the domain theory has been adapted by [Mortensen et.al. 2001] and extended to yield the Product Family Master Plan (PFMP) method. This method is suitable to take such a "picture". The method maps the product assortment between the transformation-, organ- and part domain. The model may handle the whole product family, with all of its variants. It list and view the product assortment in a holistic way, but it does not say anything about what to do to improve the company's economy of scope or about the related supply chain that is part of the realising the products. [Du et.al 2003] present also a similar "language", graph grammar, in generating product variants, their attentions are more on configuration side rather than the early conceptual phases. The focus is on organising of data and knowledge rather than on the product development process.

3 Design methods

To develop a successful product is difficult even when only a single product is to be designed. Considering multiple products at the same time is far more complex. To prevent designers from being overwhelmed with information and demands, it may be helpful to view the challenge from multiple sides. [Jiao and Tseng 1999] presented a model that considers the PFA from three different points of view; a Functional view, a Technical view and a Physical view. The functional view represents the customer side, where the customers interests are the focus, including addressing all customer requirements, against which product strategies are defined and competitors are analysed. The technical view handles the implementation of the technology, solution principle and how the products are designed. The physical view looks at handling the manufacturing side where design for manufacturing and the production equipment are evaluated until the products are realized. A modified version of this model has been adopted in order to illustrate the research topics that are covered in the selected articles. The modification relates to make the transaction between the views smooth. Fig. 2 illustrate the authors opinion on were the discussed articles have positioned them selves. The articles are also indicated at which focus areas they have; modular and/or platform). This figure must also bee seen as one layer related to the operational side, compared to the strategic level. Articles positioned between the physical and functional view axes covering life phases related to sale, maintenance and recycle have only in minor extend been commented, as they are part of more comprehensive methods.

As always the articles are written by persons with different background, where some aim the methodology at consumer products while others look at high performance industrial products. Creating a PFA involves two major approaches; Modular design and platform design. Finding the appropriate strategically approach for the company has been discussed by [Maier and Fadel 2001]. A well-defined strategy is important to establish before the design is implemented.



		Modular	Platform
1. Ho & Tang	(1998)	X	X
2. Robertson & Ulrich	(1998)	X	X
3. Krishnan et.al.	(1999)		X
4. Ericsson & Erixson	(1999)	X	
5. Mortensen et.al.	(2001)	X	X
6. Yu et.al.	(1999)	X	X
7. Otto & Wood	(1998)	X	X
8. Martin & Ishii	(2002)	X	X
9. Jiao & Tseng	(1999)	X	X
10. Gonzales-Zugasti et.al.	(2000)		X
11. Huang & Kusiak	(1998)	X	
12. Gershenson et.al.	(1999)	X	
13. Sudjianto & Otto	(2001)	X	
14. Palani Rajan et.al.	(2003)	X	X
15. Gershenson et.al.	(2003)	X	
16. Simpson et.al.	(2001)		X
17. Dahmus et.al.	(2001)	X	
18. Kokkolaras et.al.	(2000)		X
19. Gu & Sosale	(1999)	X	
20. Jiao & Tseng	(2000)	X	
21. Salvador et.al.	(2002)	X	
22. Meyer & Dalal	(2002)		X
23. Jiao & Tseng	(2004)		X
24. Jensen & Hildre	(2004)		X
25. Gupta & Krishnan	(1998)	X	X
26. Lee & Saito	(2002)		X

Figure 2: The author's opinion on where the articles are positioned, when [Jiao and Tseng 1999] points of views are used. Methods that are scattered in these view points are marked with *

[Maier and Fadel 2001] methods aid managements and designers in determining which type of product family that is appropriate based upon earlier knowledge. In this context they propose seven different types of product families, from single and evolving single products to mixed evolving mutating product family. The method find the manufacturing paradigm to the company, which relate the companies to four groups mass production, mass customisation, continuous improvement or invention. All the seven types of product families are then mapped to one or more of strategies regarding; single design, product platform design, scaling design and modularity design. Implementing such a strategy to design a product family is usually not the first thing a company does, they usually have a history of single products that have evolved over time. [Ulrich and Robertson 1998] discuss how a company can change from doing "one at a time" product over to managing product platforms. They provide partly a step by step description of the product platform planning, with focus both on the products (in a wide perspective) and the design team challenges. One of the main reasons for designing a product family is to get some economical benefits. In many of the articles this link between the design and the economical aspect is based on others knowledge in that this should give a economical advantage. [Krishnan et.al. 1999] address this important subject. They provide a model capturing the cost of product platform development project and the marked demand. The model chooses the best suitable product variants from a set of candidates.

Performing benchmarking of in the house products and the competitors may gain valuable information as well as reversed engineering. [Otto and Wood 1998] proposed a method for reversed engineering based on traditional product design for single products, but the method also looks into many aspects that may be vital in designing a product family. Understanding and establishing the correct customer needs is clearly important to design a successful product. [Yu et.al. 1999] follows this approach and present a method to define the portfolio architecture based only on customers' demand. Their method seeks to find the best architectural approach in more or less the same way as [Maier and Fadel 2001], but they neglect the design and manufacturing costs. The focus is on establishing a statistical view, with distribution of customers needs over time. From the shape of the statistical distribution, different architecture for each features in the product are proposed (Platform generation, fixed portfolio architecture, platform family or adjustable portfolio architecture). A statistical approach to guide the typology of the portfolio requires a large customer group to gather enough needs. This makes this approach perhaps more useful for consumer product rather than industrial products, where such data may be hard to get.

3.1 Modularity design methods

Modularity design arises from decomposition of a product into parts and subassemblies. Independency between these elements is the core elements in modular design and hence the product functions must be grouped. [Pahl and Beitz 1996] propose this classification:

- Basic functions are fundamental to a system and in principle not variable. They are implemented in the basic module and are essential
- Auxiliary functions are usually also of the "essential type"
- Special functions are usually implemented in separate modules that are of the "possible" type
- Adaptive functions are necessary for adaptation of other systems. These are of "essential" or "possible" type.
- Customer specific functions are usually designed individually and adapted to the system in a non module.

[Stone et.al 2000] proposed a method to identify modules from the functional structure, by consider the dominant flow, branching flow and conversion flows. [Sudjianto and Otto 2001] have extended the use of a functional structure too also model a family across different brands as well as within one brand, fig. 3. The impact on brand width on brand share is discussed in [Ho and Tang 1998].

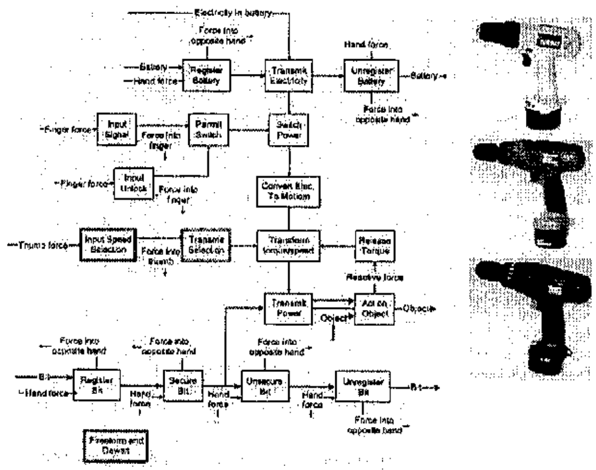


Figure 3: Cordless drill family functional structure for Black & Decker, Firestorm and Dewalt. All unshaded boxes are shared across all models [Sudjianto and Otto 2001].

[Dahmus et.al 2001] proposes a method for architecting a product family that shares interchangeable modules. Their method consists of developing a functional structure for each of the separate products and then finding the common functions structure for the family. The family function diagram consist of all the single diagrams and all the flows interactions (electrical, mechanical, gas and fluids). The flows path through sub functions defines the modules. To visualize the whole family structure they introduce a modularity matrix. The neat thing about this method is that it is easy to use and can be used across product classes. Since the method is based upon a functional decomposition of the product structure, the products in the family must have an easy dividable functions structure. The method deals only with the early phases of establishing a PFA. Functional structure modelling is a common way of establishing modules. [Huang and Kusiak 1998] use also this approach in defining the modules. They use flow and force interactions illustrated in a matrix to categorize the different modules. By using matrixes possible separate and swappable modules are identified for electro, mechanical and electromechanical components. The method is suitable for early conceptual design and on structures that can form many modules. Therefore it may be most appropriate to use in electro or the combined electromechanical field.

A slightly different approach to finding the most suitable modules in the product has been done by [Ericsson and Erixon 1999]. They use the Quality Function Deployment to ensure that the correct requirements are derived from the customer. The functions are listed in a hierarchical structure, decomposing it down to independent structures/parts. These independent technical solutions together with their modular drivers (the reason to form a module), gives the possibilities to group and find appropriate modules. In their modular drivers' development and design, variance, manufacturing, quality, purchase and reuse or other reasons may be used to form the modules. Their method uses a very holistic approach to find and establish the modules; however they do not go in depth off how the grouped technical solutions should form the modules or how the functional flows are within the product. [Salvador et.al 2002] are also discussing the production side of products based on modularity. Their research looks into different modularity options on providing cost efficient solutions when the production volume is high or low. A measure for evaluating the commonality at the component level and on the process level has been proposed by [Jiao and Tseng 2000]. The process commonality index measures the level of commonality present in the manufacturing, by finding the component that uses the same manufacturing process and introducing the set-up time (cost) for the tools. This index gives then information about which parts or modules that should be worked on, in order to reduce the cost. This type of information may be very helpful if the set-up time is an essential cost driver for the analysed products and also to give the process commonality that is present a value. [Gu and Sosale 1999] focus their attention on creating modules by looking at the strength of connections between the parts in the product. They use an algorithm and matrixes to find the best suitable modules for many different life cycle phases. Their method does however find the modules out from the relationship listed in the matrixes. Modules that are proposed may not be possible to form. [Gershenson et.al. 1999] view also the modules from multiple view points as Ericsson and Erixon. The modules are created with regard for both the functional aspect and the life –cycle process (manufacturing, service and recycling). The modules are viewed both from function and process independence or similarity. A component tree and process graphs are generated to describe the product at different detail levels. A matrix describes the similarities and dependencies for the components and processes, leading to the modules. The methods opens up for designing the modules at different detail level, since an extensive dividing of the modules will at some level make the structure not modular. The modularity performances are also measured by an index's.

3.2 Platform design methods

The other major approach to establish the PFA is by using a product platform structure, from which variants are leveraged. The main purpose of the product platform design is to increase the internal commonality and increase the external variety. Product platform is therefore a base that is developed to be the fundamental part of many products delivered to the marked over a time or/and in different categories (High cost & performance, mid range and low cost & performance). [Meyer 1997] describes this in a marked segmentation grid, where the platform may be of a vertical type (platform I), a horizontal type (platform II) or a combination, fig. 4. With the defined type of platform the work of establishing architecture may be started. [Ulrich and Eppinger 2004] propose a general method and the basic ideas of establishing a platform architecture, that also may consists of modules. The method is based on functional flow modelling to establish the chunks and identifying of the interactions between the chunks. They also indicate the important of the product architecture in the performance of the supply chain, but this is only briefly discussed.

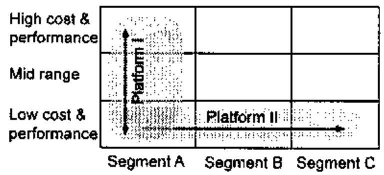


Figure 4: Marked segmentation for platform design, [Meyer 1997]

An overall approach of a platform design process is proposed by [Gonzalez-Zugasti et.al 2000]. They discuss the approach to implement a product platform design on a conceptual stage. [Martin and Ishii 2002] present also a comprehensive design for variability method, stretching from the conceptual phase and into a detail description of the products variability. Their method find index related to the amount of redesign a component required to meet future requirements and an index telling the couplings strength between neighbouring components. The methods uses well approved methods that are combined with assumption of the future direction. The method gives valuable information of the changeability the design has without needing too much detailed information. What the method does not cover is discussions around using commonality in the production processes related to establish the architecture. A different method, not so complex is proposed by [Rajan et.al 2003]. Their designs for flexibility method also establish a list of potential changes and effect of these changes. They have also adopted a traditional tool from "single" product development, the FMEA (failure mode effect analysis) and converted it to a Change Mode & Effect Analysis (CMEA). The CMEA gives indexes on design flexibility and potential for change. This method take also in to consideration the readiness the company is to perform these changes, but this is only stated as a rough assumption. Suggestions of improvement on the design or manufacturing are not covered.

To establish a well evaluated design a proper trade of analysis of all the alternatives should be conducted. [Simpson et.al 2001] have looked at scalable product platforms, where they compare a very comprehensive trade of analysis. They use a scalable electromotor as a case and iterate to the optimal platform. Further they compare this to single developed electro motors under the same conditions. The advantages and disadvantages of the performance to the PFA are discussed and they also include some manufacturing considerations. The numbers of variables to meet the requirement are evaluated against the commonality that can be acquired in the manufacturing. [Kokkoloras et.al 2002] also propose a trade off method using a cascading approach that also gives results directly comparable to the requirements. The product family is mathematically modelled and detail input is provided so that the results may come out as weight and stiffness, in their case. Performing a valuable analysis must therefore have good input to secure that results are trustable. Modelling the product family mathematically may also be difficult in some cases, while very suited in others.

All the above-mentioned methods focus merely on the section functional and technical views of establishing a PFA. The manufacturing that must be there in order to create the final products are only commented or inadequately discussed. The product used in examples and cases also consists of many components and/or sub-assemblies. This approach excludes many products that do not have a large assembly structure. [Meyer and Dalal 2002] introduce the platform architecture method for nonassembled products (film and integrated circuit). Their approach aim at understanding the dynamics of process intensive platforms and evaluate the performance. They do not present a specific method of platform design for nonassembled products, but they introduce the possibility. [Lee and Saitou 2002], and many others have discussed design and the products meeting with production for a long time, but not so in depth of a PFA. The subject that has been discussed in [Ho and Tang 1998] is the power full effect of delayed product differentiations. The assembly sequence is a key theme to address in optimising the supply chain. Product variations have a tendency to demand rapidly changes in the production. [Jiao and Tseng 2004] methods measure the flexibility a process (manufacturing) platform has to adapt to customise products. They use the manufacturing cycle time to measure this. A slightly different approach to evaluate the designs solutions space (variability) against the manufacturing process, have been proposed by [Jensen and Hildre 2004]. Variance in the design is compared with the flexibility to the manufacturing processes. The needed change in the processes due to the design variation is evaluated and gives an index indicating the estimated cost of change. [Gupta and Krishnan 1998] focus on establishing the optimal assembly sequence for a product family. Their method tries to maximize the commonality in the assembly sequence and minimize the number of subassemblies. The method may be used both for modular design, platform or a combination. To utilize the method the PFA have to be established with constraints in order to be able to execute an algorithm. A defined architecture must therefore be present before this method can be applied. It also treats all connections in the assembly with the same complexity. Introducing the assembly sequence as an important section of designing a PFA, and it plays an important role in establishing an optimal economy in the production.

4 Advantages with design for modularity and platform

The major difference between using modular or a platform approach to establish a PFA lays in the type of marked the product meets. Both [Meyer 1997] and [Simpson et.al 2001] propose that modular product facilitate horizontal leverage strategies while product platform (scalable) may facilitate vertical leverage strategies, fig. 4. Establishing a PFA based on modularity has several advantages when it comes to developing custom specified products, ease the manufacturing process and considering the life-phases of the product. Modularization can be done when focusing on these different aspects. Modules can be swapped, removed or added after request and they are used across the whole family. The customer may change the functions of the product by changing modules, but the weight and volume may be larger than compared with an integral architecture or a platform approach, due to the need to make the modules independency and interconnections. For the manufacturer a late differentiation of the product, lowers the buffer inventories and simplifies the manufacturing processes, [Lee and Tang 1997]. This enhances the internal commonality and is a key issue in effective manufacturing for both modular- and product platform designs. Preparing custom build product from an existing modular design may not be easy, if the required modular structure does not fit. The life span for a modular family must also match the effort used to establish it, [Pahl and Beitz 1996]. A more comprehensive review of product modularity definitions and advantages has been studied in depth by [Gershenson et.al. 2003].

Product platform based design has several different abstraction levels, from; common parts to common technology (manufacturing, know-how). The major focus has been on part reuse, but recently focus is also on reuse in the manufacturing and the rest of the supply chain, thus not as inclusive as for the modular approach. This new focus leads to even greater enhance of economy of scale, by reducing manufacturing and inventory cost as well as overall design cost, [Simpson et.al 2001]. The performance of a product platform may also be adjusted with the level of commonality. Similar economy benefits are found when the product platform is based on using common technology and know how to establish the PFA. The technology used should then be state of the art and ahead of the competitors.

5 Concluding remarks

Designing a product family is a topic that has been extensively covered in the last year, and specially related to modular design. This review presents some of these well recognized methods in the field of variant design, both related to modular design and product platform design. Various approaches in variant design have through the years been proposed, some very general, other highly specialised and other very related to the profession. The author has therefore indicated where in the life phases and in what topic the different methods cover. The point of views have been related to the; Functional view, Technical view and Physical view. The major group of the methods are however focused around the functional- and technical view, transforming the customer's needs into the product and its variants. These methods work also best when the product consist of an assembly of parts. The product platform approach has only briefly moved into the field of nonassembled products. There is also a lack of taking the full step into evaluating the manufacturing side and later life phases of the product family, creating a holistic view of the product family all the way from the customer's voice to the late life phases.

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